

REVIEW

Open Access



Medicago sativa for climate-smart agriculture and soil sustainability: a review

Alemu Gashe Desta^{1*}

*Correspondence:
alemu_gashe@dmu.edu.et

¹ Department of Animal
Science, College of Agriculture
and Natural Resources, Debre
Markos University, Debre Markos,
Ethiopia

Abstract

Medicago sativa is a globally significant perennial forage legume valued for its high productivity, nutritional quality, and multifunctional role in climate-smart agriculture. This review synthesizes evidence from 130 peer-reviewed studies across 35 countries, spanning temperate, subtropical, and semi-arid agroecological zones, to (i) assess the agronomic performance and productivity of *Medicago sativa*, (ii) evaluate its nutritional and environmental contributions to sustainable livestock systems, and (iii) identify research and policy priorities to enhance its adoption under climate change. Quantitative data indicate dry matter yields of 12–25 t ha⁻¹ yr⁻¹, with higher yields in irrigated temperate systems and greater variability in rain-fed, semi-arid and tropical environments. The crude protein content ranges from 15 to 25% of dry matter, supporting high digestibility (> 70% in vitro) and efficient feed conversion in ruminants. Through symbiosis with *Sinorhizobium* spp., biological nitrogen fixation of 150–300 kg N ha⁻¹ yr⁻¹ reduces dependence on synthetic fertilizers and improves the soil fertility. Long-term studies report soil organic carbon increases of 0.3–0.8 t C ha⁻¹ yr⁻¹, reflecting contributions from deep roots and rhizodeposition. The deep-penetrating root enhances drought tolerance, nutrient capture, and soil structure, thereby supporting resilience in degraded and water-limited environments. Therefore, *Medicago sativa* enhance feed security, promotes low-emission livestock production, and contributes to climate change mitigation. Future priorities include breeding for stress tolerance, improving pest and disease management, strengthening seed and extension systems, and implementing policies to support sustainable adoption, particularly in tropical and sub-Saharan African regions.

Keywords: Agronomy, Biomass, Climate-smart agriculture, *Medicago sativa*, Nutrition

1 Introduction

Globally, forage legumes are recognized as vital components of sustainable livestock production systems, offering resilience against challenges such as climate change, land degradation, and feed shortages [1]. Among these, *Medicago sativa* L., commonly known as alfalfa or Lucerne, holds a prominent position due to its widespread cultivation and significant agronomic and nutritional advantages. This perennial legume is highly valued for its deep-root system, which enhances drought resilience, high biomass yield, and superior crude protein content, making it an excellent feed resource for livestock [2].



© The Author(s) 2026. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Beyond its nutritional value, *Medicago sativa* plays a critical role in integrated crop-livestock systems by improving soil fertility through biological nitrogen fixation and supporting sustainable agricultural practices. Consequently, its cultivation aligns with the principles of climate-smart agriculture, contributing to both the productivity of livestock systems and the long-term health of agricultural ecosystems [3].

Unlike annual legumes such as *M. polymorpha*, *Medicago sativa* is characterized by its multi-year lifespan, persistent productivity across growing seasons, and adaptability to diverse agroecological zones ranging from temperate to semi-arid environments [4]. It demonstrates notable tolerance to drought conditions due to its extensive taproot system and capacity for osmotic adjustment, traits that have been well-documented in ecophysiological studies [5]. In tropical and subtropical regions, research shows that heat-tolerant and photoperiod-insensitive cultivars of *Medicago sativa* can maintain satisfactory biomass production and forage quality under high temperatures and variable rainfall, outperforming several annual and perennial tropical legumes [6, 7].

Medicago sativa is particularly suited to CSA because it enhances year-round forage availability and reduces reliance on synthetic inputs, including fertilizers and supplementary feeds. Moreover, its use in intercropping and rotational systems has been shown to improve soil structure and suppress weed pressure, contributing to sustainable land use and resource efficiency [8]. In tropical cropping systems, intercropping *Medicago sativa* with maize, sorghum, or tropical grasses has been shown to enhance total system nitrogen and biomass productivity, while improving soil fertility and mitigating erosion [9, 10].

Nutritionally, *Medicago sativa* is a superior forage, rich in digestible protein (15–25%), key minerals such as calcium, magnesium, and potassium, and containing favorable fiber fractions (neutral and acid detergent fiber) that enhance digestibility and intake [11, 12]. These traits collectively support livestock performance, including increased milk yield, weight gain, and reproductive efficiency [13]. Additionally, in tropical and subtropical systems, early-cut or multi-cut regimes optimize crude protein and digestibility, compensating for potential reductions in nutrient quality caused by heat stress or accelerated lignification [14–16]. Beyond its nutritional role, *Medicago sativa* contributes to climate change mitigation by reducing enteric methane emissions [17] and sequestering soil carbon through its deep root system, providing both production and ecological benefits [18].

While the advantages of *Medicago sativa* are well-established, knowledge gaps remain regarding its multifunctionality in resource-limited CSA systems, particularly in sub-Saharan Africa, South Asia, and tropical Latin America [19, 20]. Emerging research highlights the potential of drought-tolerant cultivars, low-lignin varieties, and optimized rhizobial symbiosis to improve persistence and forage quality in tropical and subtropical regions. Advances in genomics, phenotyping, and precision agronomy provide pathways for selecting stress-resilient genotypes and improving adaptation to local climatic and edaphic constraints [20–22].

Medicago sativa demonstrates unique attributes that make it particularly suitable for enhancing livestock productivity while contributing to soil health. Its deep-rooting system, high biomass yield, superior crude protein content, and broad climatic adaptability distinguish it from other legumes, positioning it as a cornerstone species for

climate-smart livestock systems and sustainable land management. This review emphasizes these distinctive traits and explores their potential to address feed scarcity, improve soil fertility, and support resilient livestock production under changing environmental conditions.

2 Review methodology

2.1 Literature search strategy

A systematic literature review was conducted to identify studies on *Medicago sativa* and its role in climate-smart livestock systems and sustainable soil management. Searches were performed in major bibliographic databases, including Scopus, Web of Science, and PubMed, using comprehensive Boolean search strings. Search combinations included (“*Medicago sativa*” OR “alfalfa”) AND (“climate-smart agriculture” OR “forage legume” OR “livestock feed”) AND (“soil fertility” OR “nitrogen fixation” OR “drought tolerance” OR “carbon sequestration”). The review focused primarily on recent research, with 94.6% of studies published between 2020 and 2025, while 5.4% of earlier studies were included to provide essential background and historical context. Additionally, reference lists of identified publications were screened to capture further relevant studies, ensuring inclusion of both recent and foundational literature on the agronomic performance, nutritional value, ecological functions, and climate adaptation of *Medicago sativa*.

2.2 Inclusion and exclusion criteria

Publications were selected based on clearly defined inclusion criteria to ensure methodological rigor and relevance. Included studies were (i) peer-reviewed journal articles, (ii) 94.6% published between 2020 and 2025, (iii) written in English, and (iv) focused directly on *Medicago sativa* in relation to forage production, livestock nutrition, soil improvement, or climate-smart agriculture. Both experimental and review studies reporting quantitative or qualitative findings were considered, with particular attention to studies highlighting environmental benefits or stress adaptation. Excluded were non-peer-reviewed materials, reports lacking transparent methodology, studies focusing exclusively on other legume species, and research unrelated to agricultural applications of *Medicago sativa*.

2.3 Screening and quality assessment

The study selection process followed the PRISMA guidelines, with the number of records identified, screened, included, and excluded recorded and presented in Fig. 1. Two independent reviewers screened the titles, abstracts, and full texts, with discrepancies resolved through discussion to ensure consistency and reduce selection bias. The quality of the included studies was assessed using a standardized scoring protocol that considered the study design, sample size, clarity of methodology, and robustness of the results. Each publication was scored, and only studies that met a predefined quality

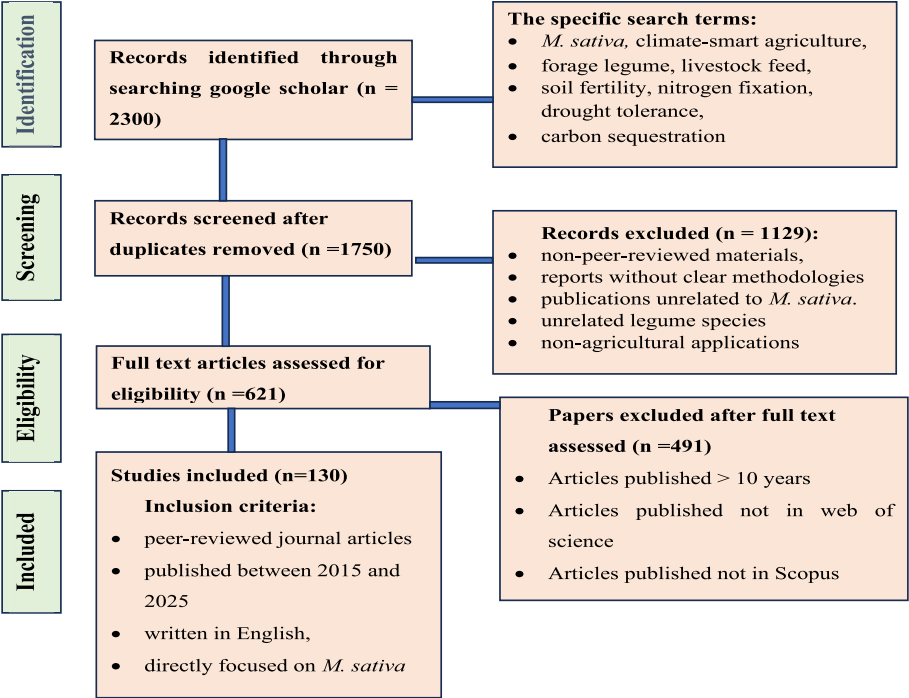


Fig. 1 PRISMA flow diagram of literature selection

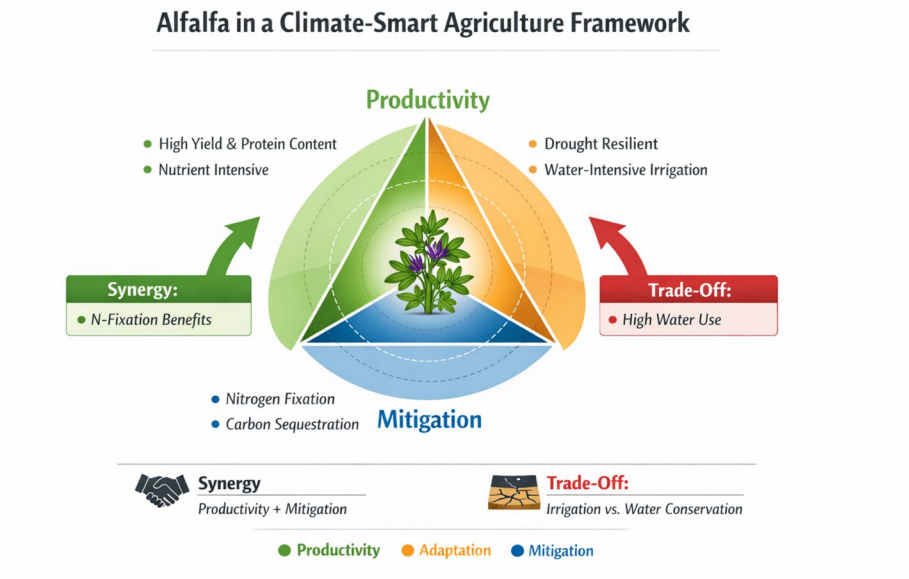


Fig. 2 Climate-smart agriculture analysis of Medicago sativa

threshold were included in the synthesis. Potential biases arising from the inclusion and exclusion criteria, such as language restrictions or database selection, are acknowledged and discussed to maintain transparency.

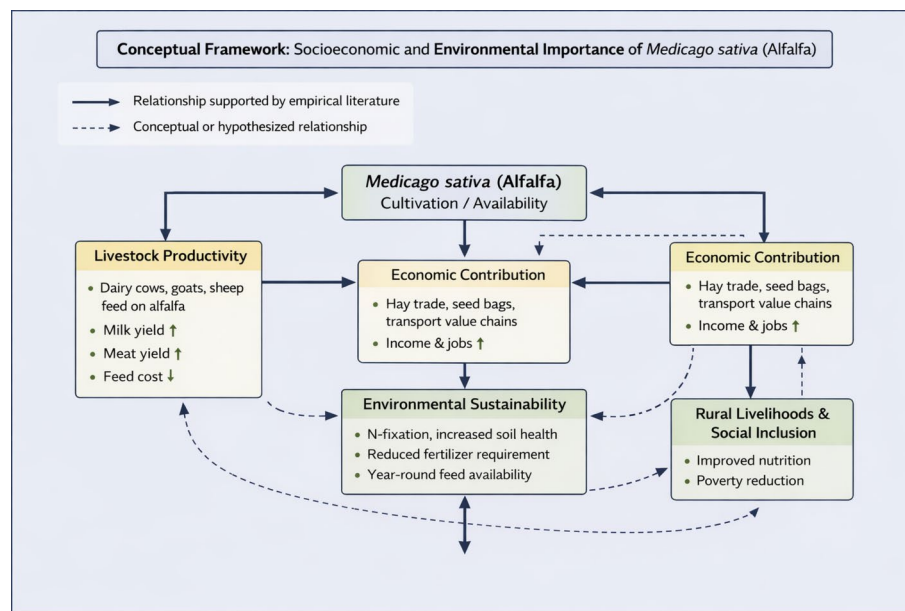


Fig. 3 Socioeconomic importance of *Medicago sativa*

3 Literature review

3.1 Climate-smart agriculture of *Medicago sativa*

Within the CSA framework (Fig. 2), *Medicago sativa* contributes substantially to the productivity by providing high-yield, nutrient-dense forage that enhances livestock growth, milk, and meat output [1, 6, 11, 13, 23, 24]. Its deep, branched root system and efficient nutrient uptake mechanisms enable stable biomass production across diverse agroecological zones, including saline and drought-prone areas, thereby improving yield reliability under climatic stress [2, 17, 20, 25–29]. Symbiotic nitrogen fixation with *Sinorhizobium medicae* and efficient phosphorus and potassium utilization further enhance forage quality while reducing the reliance on synthetic fertilizers [3, 4, 22, 30]. These adaptive traits not only support resilience to water and nutrient limitations but also facilitate integration into mixed and intercropping systems, promoting land-use efficiency and biodiversity. Nonetheless, trade-offs exist: while irrigation can maximize yield, water-intensive management may conflict with sustainable water conservation goals, highlighting the need for site-specific CSA practices in the region [31–33].

Medicago sativa also addresses the mitigation of CSA by improving nitrogen-use efficiency, reducing greenhouse gas emissions, and enhancing soil carbon sequestration. Bioactive compounds, such as tannins and saponins, contribute to reducing enteric methane emissions from ruminants, providing direct environmental benefits [18, 34–36]. The combination of high productivity, ecological resilience, and emissions reduction illustrates the synergistic potential of *Medicago sativa* in CSA systems. However, these benefits must be balanced against potential trade-offs, including the energy and water inputs required for the intensive forage production. Overall, framing *Medicago sativa* explicitly within the CSA pillars highlights its multifunctional role in climate-resilient,

nutrient-efficient, and economically viable agropastoral systems, while underscoring the importance of integrated management strategies to optimize trade-offs and maximize synergies [1, 37, 38].

3.2 Socioeconomic importance of *Medicago sativa*

Medicago sativa plays a pivotal socioeconomic role (Fig. 3) as a foundation crop in global livestock-based economies due to its remarkable nutritional value, adaptability, and contribution to rural livelihoods. It is widely regarded as the “queen of forages” because of its high crude protein (15–25%), digestible fiber, vitamins, and minerals that enhance animal growth, reproduction, and milk yield, thus improving the efficiency and profitability of dairy and meat production systems [6, 23, 39]. By reducing the dependency on expensive commercial feed supplements, *Medicago sativa* helps smallholder farmers minimize production costs and achieve feed self-sufficiency, particularly in developing countries [39, 40]. Its consistent availability as green fodder, hay, or silage provides year-round feed security, ensuring steady livestock productivity even during dry seasons [24, 39]. The crop also supports diverse livelihood opportunities such as forage seed production, hay trading, and animal fattening enterprises creating income and employment across the agricultural value chain [39, 41]. In major *Medicago sativa* producing regions like the United States, Argentina, and China, the crop contributes billions of dollars annually to the agricultural GDP, reflecting its strong economic footprint and export potential [39, 42].

Beyond its direct market value, *Medicago sativa* contributes significantly to rural development, gender inclusion, and poverty reduction through small-scale livestock enterprises and cooperative feed ventures [43]. Its integration into mixed crop-livestock systems enhances household resilience by diversifying income sources and stabilizing food supply chains [31]. In Ethiopia and other parts of sub-Saharan Africa, the expansion of *Medicago sativa* cultivation has been associated with improved dairy productivity, higher household incomes, and better nutrition outcomes due to increased milk availability [23]. Additionally, as a perennial legume, *Medicago sativa* reduces production risks by lowering input costs for fertilizers through nitrogen fixation and providing a reliable forage base that supports pastoral and agro-pastoral economies [44]. The growing interest in *Medicago sativa*-based value chains, supported by policy incentives and private investment, further underscores its importance in achieving sustainable livestock development and rural economic transformation [39].

3.3 Agronomic importance of *Medicago sativa*

Medicago sativa belongs to the Fabaceae family, subfamily *Papilionoideae*, and tribe *Trifolieae* [39]. It is a perennial legume with a penetrating root system that may extend up to 4–6 m, enabling access to deep moisture and conferring drought tolerance [45, 46]. Its trifoliate leaves, arranged alternately, enhance nitrogen fixation and photosynthesis, while inflorescences bear predominantly purple to blue flowers, with white and yellow variants in some cultivars [47]. The small, kidney-shaped seeds possess a hard coat that ensures dormancy and longevity in soil, contrasting with the short-lived seeds

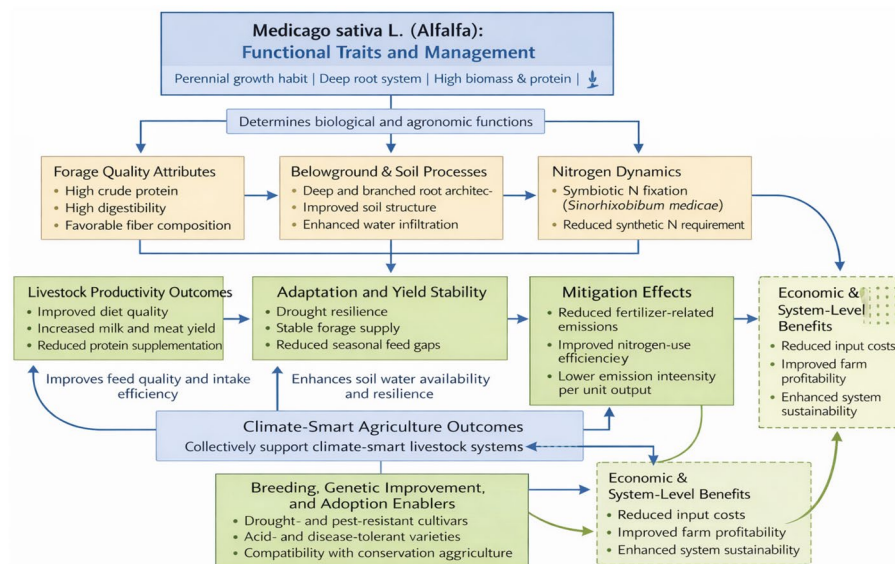


Fig. 4 Agronomic importance of *Medicago sativa*

of *Trifolium pratense* (red clover) [48]. *Medicago sativa* exhibits an erect to semi-erect growth habit and an indeterminate flowering pattern, allowing multiple harvests annually under favorable conditions [49]. Its phenology depends on photoperiod and thermal time for flowering, with vigorous vegetative growth in spring and early summer in temperate regions [5]. Unlike annual legumes such as *Vicia villosa*, *Medicago sativa* remains productive for 3–7 years, though yield declines over time due to root and crown diseases, necessitating breeding for durable cultivars [50].

Medicago sativa thrives across diverse soils, preferring well-drained loams (pH 6.5–7.5) but tolerating pH 5.5–8.5 when inoculated with *Rhizobium meliloti* [20]. It tolerates calcareous and saline soils better than *Lotus corniculatus* [51], though it performs poorly on acidic, waterlogged, or heavy clay soils [25]. Optimal growth occurs between 18 and 28 °C, and the crop withstands –10 °C to –15 °C during dormancy [52]. Annual rainfall requirements range from 400 to 1200 mm, often supplemented by irrigation in arid and semi-arid regions [26, 53].

Its adaptability from sea level to 2,500 m in areas such as the East African highlands and Andean regions underscores its ecological breadth compared to altitude-restricted species like *Trifolium repens* [51, 54]. Originating in the Mediterranean Basin, *Medicago sativa* is now globally distributed across temperate and subtropical regions due to its agronomic value and domestication history [8, 26]. Its versatility supports use in monoculture hayfields (U.S.), mixed cereal-forage rotations (North Africa), and agro-pastoral systems (East Africa) [20]. In tropical and subtropical regions such as Brazil, India, and parts of Southeast Asia, research shows that heat-tolerant cultivars of *Medicago sativa* can maintain satisfactory dry matter yields under prolonged high temperatures and variable rainfall, outperforming several annual legumes in both biomass and persistence [7, 37, 55]. Unlike narrowly adapted legumes such as *Stylosanthes* spp., *Medicago sativa* exhibits wide vertical (elevation) and horizontal (latitude) plasticity, with broad germplasm diversity supporting its role in climate-smart livestock systems [50].

3.3.1 Contribution to sustainable crop-livestock systems

The agronomic importance of *Medicago sativa* (Fig. 4) lies in its multifunctional role as both a high-protein forage and a soil-improving crop. It enhances soil fertility through biological nitrogen fixation, which may contribute 150–300 kg N ha⁻¹ annually [21, 27, 56]. This reduces dependence on synthetic fertilizers and improves soil organic matter, benefiting subsequent cereal crops in rotation systems [57]. In tropical/subtropical settings like the Brazilian Cerrado and Indian semi-arid zones, studies report that *Medicago sativa* intercropped with grasses improves total system nitrogen use efficiency and reduces fertilizer inputs by up to 30% compared to sole grass crops [9, 38, 58]. Unlike shallow-rooted legumes such as *Trifolium pratense*, *Medicago sativa*'s taproot system improves soil structure, aeration, and water infiltration, contributing to sustainable land management in dryland, humid tropics, and highland agroecosystems [59, 60].

3.3.2 Productivity, adaptability, and comparative advantage

Medicago sativa's perennial growth habit and capacity for multiple harvests confer higher dry matter and protein yields compared to most other forage legumes. Studies show that it outperforms *Vicia villosa*, *Lotus corniculatus*, and *Trifolium repens* under both temperate and subtropical conditions due to its superior regrowth capacity and resilience to grazing [28, 61]. Under tropical conditions with well-managed cutting regimes, *Medicago sativa* has displayed competitive forage yields comparable to perennial tropical legumes like *Stylosanthes guianensis* and *Arachis pintoii*, especially where irrigation or supplemental moisture is available [6, 37, 55]. In Ethiopia's central highlands, *Medicago sativa* has demonstrated stable yields under rotational cutting regimes, making it a cornerstone for year-round feed supply. Its adaptability to both irrigated and rain-fed systems underscores its potential in bridging seasonal feed gaps, particularly in mixed crop-livestock farming systems [62].

3.3.3 Soil and water conservation functions

The long taproot system of *Medicago sativa* not only supports drought resilience but also plays a key role in erosion control and soil rehabilitation. It stabilizes degraded lands and prevents topsoil loss on sloping terrains a common challenge in East African highlands [63]. Its capacity to extract nutrients from deeper soil layers complements shallow-rooted crops in intercropping systems, enhancing overall nutrient and water use efficiency [58]. In tropical high-rainfall environments, *Medicago sativa* cover has been associated with reduced surface runoff and improved rainwater infiltration compared to bare fallow plots, thereby contributing to watershed protection [31, 64, 65]. Compared to annual legumes, *Medicago sativa*'s perennial cover reduces runoff and supports carbon sequestration, making it integral to climate-resilient forage systems [30, 32, 66].

3.3.4 Economic and agronomic interconnection

From an agronomic-economic perspective, *Medicago sativa* provides high-value hay and silage, supporting dairy and beef industries globally [13]. Its high crude protein

(15–25%) and digestible fiber make it superior to many tropical legumes like *Stylosanthes guianensis* and *Desmodium intortum* [34]. Its inclusion in forage-based systems not only enhances feed quality but also reduces reliance on imported protein concentrates. In tropical regions such as West Africa and Southeast Asia, *Medicago sativa* integration into dairy systems has improved milk yield and economic returns where reliable water and management inputs exist protection [1, 23, 67]. Consequently, its integration into rotational systems improves farm profitability while enhancing ecosystem services such as pollination and biodiversity conservation [68].

3.3.5 Breeding, improvement, and future potential

Advances in breeding have focused on developing *Medicago sativa* cultivars with enhanced drought tolerance, pest resistance, and persistence under intensive utilization [17]. Improved varieties like ‘CUF 101’ and ‘Saranac’ have shown adaptability across wide ecological ranges [69]. Recent tropical/subtropical breeding efforts emphasize heat tolerance, photoperiod insensitivity, and resistance to foliar diseases prevalent under humid conditions, broadening the crop’s adaptation beyond traditional temperate zones [3, 70, 71]. In African contexts, selection for acid-tolerant and disease-resistant genotypes is crucial for expanding *Medicago sativa* production on marginal lands. Furthermore, the crop’s compatibility with emerging conservation agriculture practices, including reduced tillage and integrated nutrient management, enhances its relevance for sustainable forage intensification [9].

3.3.6 Establishment of *Medicago sativa*

Medicago sativa exhibits moderate germination vigor, influenced by both seed quality and environmental factors such as temperature and moisture. Optimal germination occurs at temperatures between 15 and 25 °C, with good emergence typically observed in well-aerated loamy soils [25]. Establishment success varies across agroecological zones due to differences in rainfall distribution, temperature fluctuations, and soil structure. Tropical research indicates that early-morning sowing and incorporation of soil moisture conservation practices (mulching or tied ridging) significantly improve emergence in hot, dry tropic soils [1, 6, 72]. In temperate climates, early spring sowing ensures rapid root development before summer droughts. Conversely, in semi-arid and tropical highland environments like Ethiopia’s central plateau, establishment is often constrained by erratic rainfall and shallow soils [14]. Pre-sowing seed treatments such as scarification or inoculation with *Rhizobium meliloti* significantly enhance establishment rates in degraded or acidic soils [4]. Thus, while *Medicago sativa* demonstrates strong potential across diverse ecologies, tailored management strategies are required for optimal stand establishment.

3.4 Nutritional composition and contribution to livestock productivity

3.4.1 Nutritional composition

Medicago sativa, widely recognized as one of the most nutritious forage legumes, exhibits outstanding crude protein (CP) content and digestibility, making it an essential feed component for ruminants. *Medicago sativa* biomass yields vary widely from 12 to 25 t DM ha⁻¹ yr⁻¹, mainly due to environmental and management factors. Higher yields (> 20 t DM ha⁻¹ yr⁻¹) occur in irrigated temperate systems with improved cultivars and frequent cuttings, while rain-fed, semi-arid, or tropical subhumid systems with seasonal dry spells show lower, more variable yields influenced by soil fertility, moisture stress, and pest pressure [6, 72, 73]. *Medicago sativa*'s CP content ranges from 15 to 25% of dry matter (DM), depending on harvest stage, soil fertility, and climatic conditions [74, 75]. Tropical studies report that seasonal heat stress can accelerate lignification, reduce CP and increase fiber concentrations in *Medicago sativa* compared to cooler climates, highlighting the importance of adjusted cutting schedules [6, 73, 76].

Early-cut *Medicago sativa* contains higher CP and lower fiber, which enhances digestibility and energy availability compared to late-cut forage [68]. The in vitro dry matter digestibility (IVDMD) of *Medicago sativa* can exceed 70%, surpassing many tropical forages such as *Stylosanthes spp.* and *Desmodium intortum*, which generally range between 60 and 65% IVDMD and 15–22% CP [77]. Comparative tropical research shows that *Medicago sativa* harvested at optimal maturity can match or exceed the feed value of tropical legumes like *Lablab purpureus*, particularly under adequate moisture and soil fertility [36, 73]. The relative feed value (RFV) of *Medicago sativa*, which integrates digestibility and intake potential, ranks it among the top forage legumes globally, particularly in temperate and subtropical systems.

Its high CP and rapidly degradable nitrogen fractions stimulate microbial protein synthesis in the rumen, thereby enhancing nutrient utilization efficiency and improving overall livestock performance [67]. Compared to grass forages, *Medicago sativa* provides a balanced combination of energy and protein that supports rapid animal growth, higher milk yield, and better reproductive efficiency [78].

The fiber composition of *Medicago sativa*, particularly its Neutral Detergent Fiber (NDF) and Acid Detergent Fiber (ADF) contents, determines intake and energy utilization efficiency. Early-bloom *Medicago sativa* typically contains 38–42% NDF and 28–32% ADF [75], which are considerably lower than values found in tropical grasses like *Panicum maximum* and *Brachiaria spp.*, often exceeding 60% NDF and 40% ADF [62]. Despite this advantage, in hot tropical conditions delayed harvest can rapidly increase fiber content, reducing intake potential unless harvest timing is adapted [6, 73, 76].

Medicago sativa's Net Energy for Lactation ranges between 1.1 and 1.6 Mcal/kg DM [78], which exceeds that of most tropical legumes such as *Lablab purpureus* or *Vigna unguiculata* (1.1–1.3 Mcal/kg DM) [79]. These superior energy and fiber characteristics make *Medicago sativa* an ideal component for formulating balanced ruminant rations that sustain high milk production, weight gain, and reproductive efficiency. However,

Table 1 Comparative agronomic, nutritional, and ecological attributes of *Medicago sativa* versus other selected forage legumes

Attribute	<i>Medicago sativa</i>	<i>Vicia villosa</i>	<i>Trifolium pratense</i>	<i>Lotus corniculatus</i>	<i>Stylosanthes spp.</i>	<i>Desmodium intortum</i>	<i>Vigna unguiculata</i>	References
Life cycle/Growth habit	Perennial, 3–7 years; erect to semi-erect; multiple harvests per year	Annual/winter annual; shallow-rooted	Short-lived perennial; shallow-rooted	Perennial; deep-rooted	Perennial/short-lived tropical	Perennial tropical	Annual/short-lived tropical	[39, 45, 45–50, 55, 128]
Root system	Deep taproot 4–6 m; accesses subsoil moisture; drought tolerant	Shallow taproot; less drought-tolerant	Shallow taproot; limited drought resilience	Deep taproot; drought-tolerant	Moderate root depth; less drought-tolerant	Moderate to deep roots	Moderate roots; drought-tolerant	[45, 46, 51, 16, 55, 129]
Soil adaptation/pH tolerance	Loam pH 6.5–7.5, tolerates 5.5–8.5 with inoculation; tolerates calcareous & saline	Adapted to loams; sensitive to drought	Prefers fertile, moist soils	Tolerates moderate salinity & calcareous soils	Tropical soils; less saline tolerance	Acid-tolerant; tropical	Tropical soils; moderate fertility	[20, 51, 25, 115, 130]
Temperature tolerance	18–28 °C optimal; –10 to –15 °C dormancy; temperate & subtropical; 0–2,500 m a.s.l	Cool-season; less tolerant to extremes	Temperate; frost-sensitive	Temperate to subtropical	Tropical/subtropical	Tropical/subtropical	Tropical/subtropical	[20, 25, 52, 54, 116]
Rainfall/irrigation requirement	400–1200 mm annual; irrigation improves yield	Moderate rainfall; less drought tolerance	Moderate rainfall	Moderate; drought-tolerant	Tropical rainfall; irrigation often needed	600–1200 mm; irrigation improves growth	600–1200 mm; irrigation often needed	[53, 26, 61, 14, 114, 7]
Nitrogen fixation/soil fertility	150–300 kg N/ha/year; deep-rooted enhances soil; organic matter contribution	Moderate N fixation	Moderate N fixation; shallow contribution	Moderate N fixation	Moderate N fixation	Moderate	Moderate	[21, 27, 56, 30, 96]
Biomass/yield potential	12–25 t DM/ha/year; multiple cuttings	Moderate yield; annual	Moderate yield	Moderate	Moderate	Moderate	Moderate	[20, 74, 75, 116, 55]
Crude protein (CP)	15–25% DM; highest in early cuts	15–20%	15–18%	14–18%	15–18%	15–20%	12–18%	[39, 23, 6, 74, 75, 77]

Table 1 (continued)

Attribute	<i>Medicago sativa</i>	<i>Vicia villosa</i>	<i>Trifolium pratense</i>	<i>Lotus corniculatus</i>	<i>Stylosanthes spp.</i>	<i>Desmodium intortum</i>	<i>Vigna unguiculata</i>	References
Digestibility/NDMD	> 70%; superior to many tropical legumes	60–65%	60–65%	60–65%	60–65%	60–65%	55–65%	[41, 75, 77, 55]
Fiber (NDF/ADF)	38–42%/28–32% (early bloom); lower than tropical grasses	Higher than Medicago sativa; reduces intake	Moderate	Moderate; improves intake vs. grasses	Higher NDF	Moderate	Higher NDF	[11, 12, 62, 75, 55]
Energy (NEL)	1.1–1.6 Mcal/kg DM; higher than most tropical legumes	1.1–1.3	1.1–1.3	1.1–1.3	1.1–1.3	1.1–1.3	1.1–1.3	[78, 79, 55]
Anti-nutritional factors (ANFs)	Saponins → bloat; coumestrol → reproductive effects; requires mitigation	Low-moderate	Moderate phytoestrogens	Moderate condensed tannins	Moderate condensed tannins	Moderate	Low-moderate	[83, 64, 35, 83–89]
Contribution to live-stock productivity	High: milk yield, weight gain, FCE, reproductive efficiency	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	[41, 74, 73–76, 90–92]
Soil conservation/ carbon sequestration	Deep roots: erosion control, C-sequestration 0.3–0.8 t C/ha/yr	Limited due to shallow roots	Moderate	Moderate	Moderate	Moderate	Moderate	[20, 63, 97, 97–100]
Irrigation adaptability	High; used widely in Ethiopia, East Africa, Europe, North & South America	Moderate	Moderate	Moderate	High in tropics	Moderate	Moderate	[61, 14, 114, 7]

the lignification process during plant maturation reduces digestibility, highlighting the importance of harvesting at the optimal growth stage to preserve forage quality [67].

Medicago sativa also serves as a rich mineral and vitamin source, contributing significantly to animal health and productivity. It contains calcium (1.2–1.5% DM), potassium (2–2.5% DM), and magnesium (0.2–0.5% DM), as well as essential micronutrients like zinc, copper, and manganese [80]. Furthermore, it provides substantial quantities of β -carotene (vitamin A precursor), tocopherols (vitamin E), and B-complex vitamins, all of which enhance reproductive performance, immunity, and milk quality in livestock [81]. In regions where tropical soil micronutrient deficiencies are common, *Medicago sativa* forage has been observed to help alleviate subclinical mineral deficiencies in grazing animals, though supplementation may still be required for optimal performance [6, 11, 76].

However, excessive potassium can interfere with magnesium absorption, potentially leading to grass tetany in lactating cows [82]. Proper mineral balancing through diet formulation or supplement use is therefore crucial. Seasonal changes also influence nutrient composition warmer conditions typically reduce CP and energy while increasing fiber due to accelerated lignification [37].

Anti-nutritional factors and limitations

Despite its excellent nutritional profile, *Medicago sativa* poses a measurable risk of frothy bloat due to its saponins content. Experimental and observational studies consistently associate elevated saponins concentrations with increased bloat incidence; however, reported risk thresholds (commonly cited around 0.5–1.0% of dry matter) vary widely depending on animal species, intake rate, forage maturity, and experimental conditions [83]. Animals grazing pure, lush *Medicago sativa* pastures with rapid regrowth are particularly susceptible, and risk is exacerbated under high-protein, low-fiber diets that reduce ruminal mat formation.

In practical terms, bloat risk can be assessed using the “bloat potential index,” where *Medicago sativa* swards exhibiting index values above approximately 30–35% are frequently classified as high risk, although this benchmark is derived largely from regional field trials and expert consensus rather than universal physiological thresholds [64]. By contrast, mixed swards containing grasses or condensed tannin (CT)-rich legumes typically lower the index by approximately 10–20% across studies, highlighting the protective effect of dietary fiber and moderate tannins [35]. While these indices provide useful decision-support tools, their predictive accuracy remains context-dependent, underscoring the need for site-specific calibration and adaptive grazing management.

The physiological impact of *Medicago sativa*’s phytoestrogens, primarily coumestrol, also exhibits dose–response relationships. Coumestrol concentrations commonly reported in the range of 25–50 mg/kg DM have been associated with transient reproductive disruptions—including delayed estrus and reduced conception rates—in ewes and heifers [84–86]. At higher concentrations, the likelihood and severity of reproductive effects increase, though species-specific tolerance varies; for example, cattle generally exhibit lower sensitivity than sheep [65]. Importantly, these values should be interpreted as indicative ranges rather than strict toxicity thresholds, as controlled feeding trials, epidemiological evidence, and on-farm observations show considerable overlap between “safe” and “risk” concentrations. Environmental stressors such as drought,

fungal infection, or mechanical damage can elevate coumestrol levels by approximately 30–60% in affected stands, further intensifying risk [84–86]. Therefore, monitoring coumestrol levels and strategically blending *Medicago sativa* with low-phytoestrogen forages or timing harvest to avoid peak accumulation stages is critical to maintain reproductive performance.

Management of ANFs in *Medicago sativa* can be optimized using cost–benefit considerations. Incorporating anti-bloat agents like poloxalene or forming mixed-species swards incurs additional inputs but reduces veterinary costs and nitrogen losses, enhancing overall farm profitability [87]. Comparative analyses show that, relative to other high-protein forages such as soybean meal, clover, or *Lotus corniculatus*, *Medicago sativa* delivers higher total digestible nutrients but requires more proactive ANF mitigation [88]. For example, while *Lotus* can reduce protein degradation through moderate CT levels, it may limit intake at high concentrations [88], whereas *Medicago sativa* allows greater voluntary intake but increases bloat and nitrogen excretion risk. Consequently, optimizing livestock performance relies on integrating forage species selection, harvest timing, and targeted supplementation, with management decisions informed by probabilistic risk assessment rather than fixed ANF thresholds, balancing nutritional advantages against ANF-related risks and associated management costs [89].

3.4.2 Contribution to livestock productivity

The high nutritional density and balanced composition of *Medicago sativa* directly translate into enhanced livestock productivity and feed quality improvement across various production systems. Its superior crude protein (CP), digestibility, and mineral content lead to increased feed efficiency, weight gain, and milk yield in ruminants [41, 76]. For instance, studies indicate that dairy cows fed *Medicago sativa*-based diets achieve a feed conversion efficiency of 0.40–0.45 kg of milk per kg of dry matter intake (DMI), compared to 0.28–0.32 kg/kg DMI for cows on grass or low-protein legume diets [41, 76]. Similarly, lactating cows consuming high-quality *Medicago sativa* silage demonstrate a 15–20% higher body weight gain and up to 25% increase in milk protein content, reflecting the enhanced nutrient utilization and digestibility of *Medicago sativa*-based rations [41, 76].

For small ruminants such as sheep and goats, *Medicago sativa* supplementation markedly improves growth rates and reproductive efficiency. Research shows that lambs and kids fed diets containing 30–50% *Medicago sativa* in the ration exhibit a FCE of 0.18–0.22 kg live weight gain per kg DMI, compared to 0.12–0.15 kg/kg DMI in animals on grass hay or crop residue diets [73, 90]. Additionally, *Medicago sativa* supplementation reduces kidding or lambing intervals by 10–15% and increases offspring survival rates by 8–12%. Its inclusion in feed rations or mixed silages improves rumen microbial balance, fiber digestion, and overall nutrient utilization [36]. The high feed quality index of *Medicago sativa*, reflected by its CP-to-fiber ratio (ranging 1.2–1.5) and digestible energy content (11–12 MJ/kg DM), makes it an indispensable component of high-performance livestock diets and a key driver of productivity improvement in both commercial and smallholder systems [90–92].

3.5 Role of *Medicago sativa* in soil fertility, nitrogen fixation, and carbon sequestration

3.5.1 Biological nitrogen fixation

Medicago sativa plays a transformative role in improving soil fertility through its efficient symbiotic nitrogen fixation and association with *Rhizobium*. This symbiosis enables the crop to fix between 150 and 300 kg N ha⁻¹ year⁻¹ under optimal environmental and soil conditions [30]. Variability in *Medicago sativa* nitrogen fixation is influenced by soil depth, moisture, and microbial communities [93] observed that soil nitrate increased mainly in the topsoil (0–40 cm), while [10] reported significant vertical spatial variability, with *Medicago sativa* affecting topsoil more than subsoil. Measurement challenges arise from spatial differences in nutrients and microbiomes, as noted by [94]. Environmental factors like light and temperature also affect fixation rates, with [95] showing that higher blue light reduced dry mass via stomatal regulation. Such biological nitrogen fixation (BNF) substantially reduces dependence on synthetic nitrogen fertilizers, contributing to environmentally sustainable agricultural systems. Compared with other legumes, *Medicago sativa* exhibits superior nodulation vigor, deeper root penetration, and greater nitrogen transfer efficiency, enhancing nutrient availability even in subsoil horizons [96]. The nitrogen fixed by *Medicago sativa* not only enriches the soil for subsequent crops in rotation but also enhances soil organic matter and cation exchange capacity, improving long-term fertility and soil health.

The continuous nitrogen contribution from *Medicago sativa*'s perennial growth cycle supports sustained soil fertility far beyond the growing period, unlike annual legumes such as *Vicia sativa*, which have shorter cycles and limited residual nitrogen [9]. Additionally, the decomposition of *Medicago sativa* residues after each harvest returns organic nitrogen and carbon compounds to the soil, promoting microbial diversity and biological activity in the rhizosphere [30]. This enhanced microbial community accelerates nutrient cycling, improving soil structure and aggregation. Hence, *Medicago sativa* serves as both a nutrient pump and a soil conditioner, creating a more favorable environment for subsequent crops in integrated crop–livestock systems, particularly under resource-constrained and rain fed conditions [38].

3.5.2 Contribution to soil carbon sequestration and soil structure

Beyond its nitrogen fixation capacity, *Medicago sativa* significantly contributes to soil carbon sequestration and soil structure improvement through its extensive, deep-rooted system [64]. The species' robust taproot often reaching depths of 4–6 m enhances water infiltration and facilitates the transfer of photosynthetically fixed carbon to deeper soil layers [97]. This process results in long-term organic carbon storage, improving soil aggregation and stability. Compared with shallow-rooted forage species, *Medicago sativa* contributes a greater proportion of below-ground biomass, promoting root turnover and humus formation that underpin soil productivity and resilience [98].

In erosion-prone or degraded landscapes, *Medicago sativa* acts as a biological soil conservation agent. Its dense root network anchors the soil, minimizing surface runoff and topsoil loss while enhancing infiltration and water-holding capacity [33]. This function is

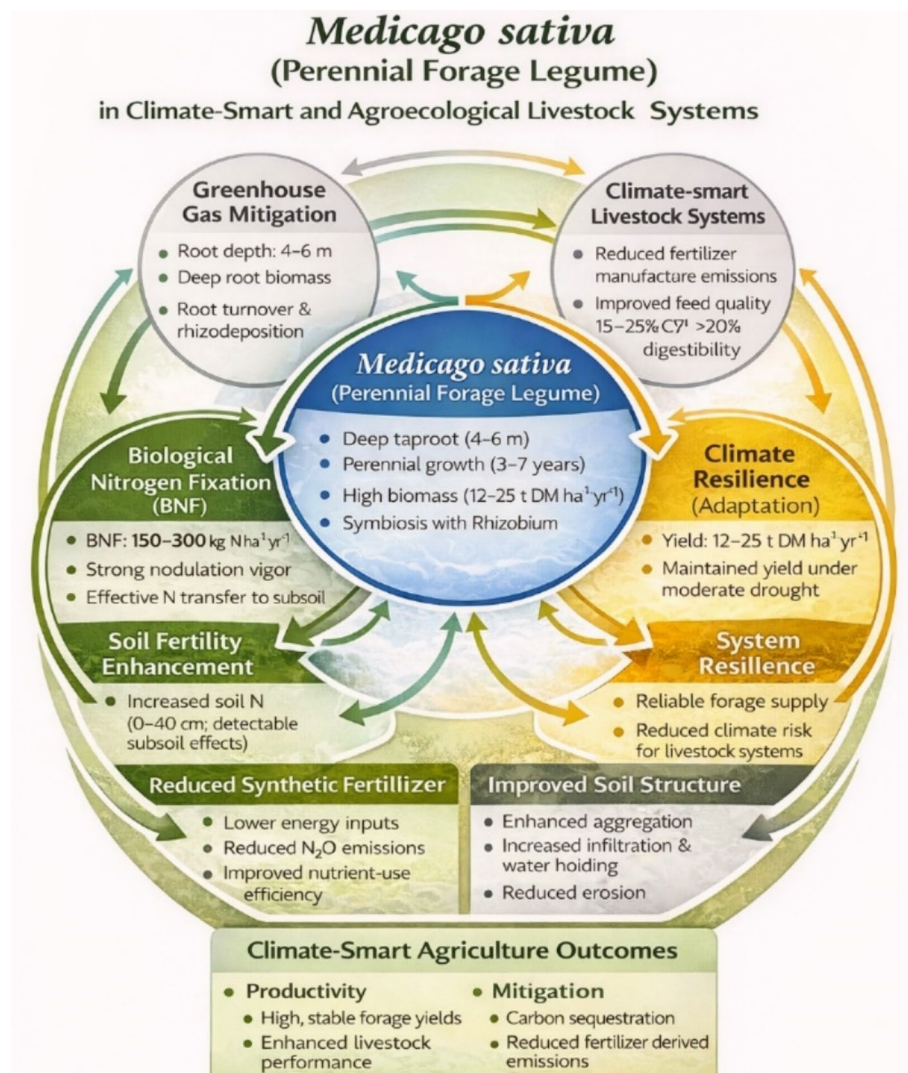


Fig. 5 Role of *Medicago sativa* in soil fertility, nitrogen fixation, and carbon sequestration

particularly valuable in semi-arid and arid environments, where water scarcity and land degradation are major production constraints. Moreover, in contrast to grasses such as *Panicum maximum*, which primarily stabilize surface soils, *Medicago sativa* improves subsoil recovery and nutrient cycling through deeper nutrient capture and organic matter inputs [99]. Consequently, its integration into agroecological restoration programs enhances multiple ecosystem services, including biodiversity conservation, nutrient cycling, and climate change mitigation [100].

3.5.3 Role in climate resilience

Medicago sativa exhibits notable tolerance to multiple abiotic stressors (Table 1) including drought, salinity, and temperature extremes making it a cornerstone of climate-resilient forage systems. Its extensive taproot system allows access to subsoil moisture,

conferring superior drought resilience compared with most forage legumes [28, 61]. Empirical studies in Mediterranean and semi-arid regions indicate that *Medicago sativa* can maintain biomass production under moderate water deficit by adjusting root architecture, enhancing osmotic regulation, and sustaining symbiotic nitrogen fixation [101–103]. However, prolonged or severe drought conditions can significantly reduce both yield and forage quality, as water stress impairs nodulation, photosynthetic efficiency, and nutrient translocation [26].

When compared with other legumes such as *Lotus corniculatus* (bird's foot trefoil), *Medicago sativa* offers a balanced trade-off between drought tolerance and high biomass yield [87]. It also shows moderate salinity tolerance, although excessive salt levels can inhibit growth and BNF [87]. Breeding efforts targeting salt exclusion mechanisms and antioxidant defense pathways have shown promising results in developing salt-tolerant *Medicago sativa* cultivars [104]. Similarly, its capacity to withstand low temperatures through dormancy induction and recover post-winter makes it suitable for a wide range of agroecological zones [15, 87, 105]. Nevertheless, genotype-specific selection remains essential to maximize productivity under diverse climate stressors [87].

3.5.4 Role in greenhouse gas mitigation

From a life-cycle perspective, *Medicago sativa* contributes substantially to greenhouse gas (GHG) mitigation across multiple stages of forage and livestock production (Fig. 5). Its biological nitrogen fixation (BNF) reduces reliance on synthetic nitrogen fertilizers, which are energy-intensive to produce and emit significant amounts of nitrous oxide (N_2O) during manufacturing, transport, and field application [30, 32, 66]. When incorporated into ruminant diets, *Medicago sativa* improves feed conversion efficiency and rumen fermentation, often lowering enteric methane (CH_4) emissions per unit of animal product due to higher digestibility and protein content [106, 107]. Long-term cultivation of *Medicago sativa* increases soil organic carbon by $0.3\text{--}0.8 \text{ t C ha}^{-1} \text{ yr}^{-1}$ through its deep-rooted system and high carbon inputs, thereby promoting sustained carbon sequestration and strengthening the role of agricultural soils as effective carbon sinks [65]. From cultivation through feed utilization, careful management of legume residues and manure is essential to avoid secondary N_2O emissions [108].

3.5.5 Integration into climate-smart agriculture

In the era of climate change, *Medicago sativa* serves as a key component of climate-smart agriculture by directly enhancing productivity. Its high nutritive value and digestibility support resilient livestock feeding systems, ensuring stable animal performance even under variable climatic conditions [20, 72]. In mixed cropping and agroforestry systems, *Medicago sativa* contributes to overall farm productivity by fixing atmospheric nitrogen, improving soil fertility, and increasing forage yield without the need for high synthetic fertilizer inputs [109, 110]. Optimal agronomic practices such as selecting high-performing cultivars, scheduling irrigation effectively, and managing cutting intervals allow farmers to maintain consistent biomass production while preserving forage

quality [111]. By sustaining high output under marginal or degraded land conditions, *Medicago sativa* operationalizes the productivity pillar of CSA.

Medicago sativa also strengthens the adaptation and mitigation dimensions of CSA. Its extensive root system, drought tolerance, and salinity resilience enable crops to maintain growth under water scarcity and other abiotic stresses [29], helping livestock systems adapt to changing climates. Integrating stress-tolerant *Medicago sativa* genotypes with regenerative soil management practices like cover cropping, organic amendments, and reduced tillage enhances system resilience and conserves soil structure [112]. In terms of mitigation, *Medicago sativa* contributes by sequestering soil carbon, reducing greenhouse gas emissions through nitrogen fixation, and lowering reliance on synthetic fertilizers [113]. Together, these mechanisms make *Medicago sativa* a practical tool for operationalizing climate-smart agriculture, balancing the trade-offs between productivity, adaptation to climate variability, and environmental sustainability [28].

3.5.6 *Medicago sativa* irrigation practices

Medicago sativa irrigated systems are widely adopted across different regions (Table 1) due to their high yield potential, nutritive value, and contribution to sustainable livestock production. In East Africa, countries like Ethiopia and Kenya have successfully integrated irrigated *Medicago sativa* systems to improve dairy productivity, particularly in peri-urban areas where water access allows for multiple harvests per year [114]. In North America, the United States, particularly in California and the Midwest, employs large-scale sprinkler and center-pivot irrigation systems for *Medicago sativa* cultivation, enabling 4–6 cuttings per year under controlled water management, thereby ensuring consistent high-protein forage for dairy and beef industries [14].

Similarly, in South America, irrigated *Medicago sativa* in Argentina and Chile contributes significantly to livestock feed security in semi-arid regions [7], where precise irrigation scheduling enhances biomass yield and persistence. Across all regions, careful attention to water availability, soil fertility, and pest management underpins the success of irrigated *Medicago sativa* systems [61], making it a globally important forage crop.

3.5.7 Comparative characteristics of *Medicago sativa* versus other forage legumes

Medicago sativa, commonly known as *Medicago sativa*, stands out among forage legumes (Table 1) due to its superior agronomic and ecological attributes. As a deep-rooted perennial with a life cycle of 3–7 years, it exhibits remarkable drought tolerance, accessing subsoil moisture through roots that extend 4–6 m, which enhances its resilience under variable rainfall conditions [20]. In contrast, legumes such as *Vicia villosa* and *Trifolium pratense* are shallow-rooted, annual or short-lived perennials, and less able to withstand prolonged dry spells [16]. *Medicago sativa* adapts to a wide range of soil types, including loams with pH 5.5–8.5 when inoculated, and tolerates calcareous and moderately saline soils, which broadens its ecological adaptability [115]. The crop thrives optimally at temperatures of 18–28 °C and can survive as low as –10 to –15 °C during dormancy, allowing cultivation in temperate and subtropical zones from sea level up to 2,500 m a.s.l. [20, 116]. Its high biomass yield potential, reaching 12–25 t DM/ha/

year with multiple cuttings, coupled with exceptional crude protein content (15–25%) and in vitro digestibility (>70%), makes it a highly nutritious forage for ruminants [20, 116]. By contrast, most tropical legumes and annuals exhibit moderate yields, lower protein content, and digestibility, limiting their contributions to livestock productivity [55]. *Medicago sativa*'s nitrogen-fixing ability (150–300 kg N/ha/year) significantly enhances soil fertility and contributes to organic matter accumulation, further improving its role in sustainable farming systems [20].

Beyond productivity, *Medicago sativa* provides substantial ecological benefits. Its deep taproot system reduces soil erosion and promotes long-term carbon sequestration at rates of 0.3–0.8 t C ha⁻¹ yr⁻¹, supporting its role as a climate-smart forage option [20]. These sequestration estimates are derived from long-term field experiments (≥5–15 years) based on repeated, bulk density-corrected soil organic carbon (SOC) stock measurements across standard depth intervals (typically 0–30 cm, and in some cases extending to 60–100 cm). Reported gains reflect SOC accumulation under continuous *Medicago sativa* stands or *Medicago sativa*-based rotations, integrating surface residue inputs with substantial belowground carbon contributions from deep root biomass and rhizodeposition.

Additionally, its adaptability to irrigated systems is well-documented across Ethiopia, East Africa, Europe, and the Americas, facilitating high and stable forage production under managed water regimes. While certain anti-nutritional factors such as saponins and coumestrol require careful management to prevent bloat or reproductive effects in livestock, appropriate harvest and feeding strategies mitigate these risks [20]. In comparison, other forage legumes including *Lotus corniculatus*, *Stylosanthes spp.*, and tropical species such as *Desmodium intortum* and *Vigna unguiculata* offer moderate contributions to livestock productivity, soil fertility, and ecological services due to shallower root systems, lower digestibility, or limited adaptation to temperate climates [20].

3.6 Challenges and limitations in adopting *Medicago sativa*

3.6.1 Agronomic and biotic constraints

Medicago sativa cultivation faces significant agronomic challenges, chiefly from pests, diseases, and establishment difficulties, which collectively reduce its productivity and profitability. Among pests, *Hypera postica* (*Medicago sativa* weevil) and *Acyrtosiphon pisum* (pea aphid) are notorious for defoliation and substantial yield losses [70]. Similarly, diseases such as Phytophthora root rot (*Phytophthora medicaginis*), Fusarium wilt (*Fusarium oxysporum*), and anthracnose (*Colletotrichum trifolii*) pose recurrent threats by compromising root and canopy health [70, 71, 117]. Establishment issues especially seedbed preparation, soil moisture deficits, and seed dormancy further compound production risks [118]. Poor seed-soil contact due to inadequate tillage or drought conditions often results in patchy stands and reduced plant density [119].

In contrast, studies have demonstrated that proper inoculation with *Sinorhizobium meliloti* strains enhances nodulation, nitrogen fixation, and establishment success [22, 120], suggesting that targeted agronomic management can mitigate some constraints. However, pest and disease prevalence differs across regions and agroecological zones.

Comparative studies between Mediterranean and temperate climates reveal varying disease complexes and pest pressures, complicating the development of universal management strategies [121]. Consequently, region-specific integrated pest and disease management (IPDM) practices remain essential for sustainable *Medicago sativa* production across diverse agroecosystems.

3.6.2 Socioeconomic and institutional barriers to adoption

Despite *Medicago sativa*'s recognized nutritive value and economic importance, its adoption remains limited in many developing regions due to inadequate awareness, poor seed availability, and the perception of complex management requirements [87, 122, 123]. Farmers often prioritize cereal or pulse crops because of familiarity, risk aversion, or limited extension support [44]. Studies conducted in Ethiopia and South Asia indicate that restricted access to certified seed and limited agronomic knowledge significantly impede the adoption of *Medicago sativa* among smallholders [122, 124]. Additionally, socioeconomic constraints such as high input costs, labor demands, and the absence of market linkages further hinder the crop's integration into smallholder systems [1].

Institutional weaknesses such as fragmented extension services and insufficient policy incentives for forage crop production exacerbate these challenges [125]. The lack of coordinated seed multiplication programs, credit access, and value chain integration discourages farmers from investing in perennial forages [126]. Addressing these barriers requires strengthening extension networks, establishing public-private partnerships for seed systems, and enhancing farmer training on *Medicago sativa* agronomy and utilization.

3.6.3 Research and technological gaps

From a research perspective, several critical gaps persist in breeding and management practices aimed at improving *Medicago sativa* productivity and resilience. Limited progress has been achieved in breeding for biotic and abiotic stress tolerance particularly drought, salinity, and heat resistance which are increasingly vital under climate change conditions [127]. While molecular breeding and genomics tools have advanced rapidly in North America and Europe, their application remains limited in many developing regions [20]. Furthermore, gaps exist in optimizing mixed cropping systems, developing effective seed treatment and inoculation protocols, and designing post-harvest forage preservation methods suited to smallholder realities [20].

3.7 Future research and policy implications

3.7.1 Future research directions

Medicago sativa (alfalfa) represents a critical forage resource for climate-smart agriculture due to its high biomass yield, protein-rich forage, nitrogen-fixing ability, and multifunctional role in soil restoration and livestock systems. Despite these benefits,

knowledge gaps and technological constraints limit its adoption in developing regions. Prioritizing research in climate-resilient cultivar development, integrated agronomy, pest and disease management, environmental assessment, and socio-economic adoption studies is justified because these areas directly address yield limitations, smallholder risk, and climate adaptation challenges [22, 70, 127]. Addressing these priorities will maximize *Medicago sativa*'s productivity, ecological benefits, and adoption potential.

3.7.1.1 Breeding and genetic improvement Short-term priorities include accelerating cultivar development through genomic selection, marker-assisted breeding, and exploration of local landraces and wild relatives. This approach targets drought, heat, and salinity tolerance, as well as pest and disease resistance traits increasingly critical under climate change [20, 127]. Long-term priorities should focus on gene editing techniques such as CRISPR/Cas9 to introduce complex traits efficiently while maintaining forage quality. Expanding multi-environment trials ensures cultivars are regionally adapted, minimizing establishment risks in heterogeneous agroecologies.

3.7.1.2 Integrated agronomy and mixed-system optimization Critical short-term research includes evaluating sowing methods, seed inoculation protocols (e.g., *Rhizobium*/AMF co-inoculation), and cutting/grazing regimes under smallholder conditions to improve stand establishment and persistence [22, 120]. Mid- to long-term studies should focus on intercropping, relay cropping, and mixed-livestock systems, which enhance nutrient and water use efficiency and reduce pest/disease pressures through diversification. These approaches also mitigate the risk of crop failure in marginal lands, providing resilient forage options.

3.7.1.3 Pest, disease, and seed health management Current knowledge gaps exist in understanding local pest and disease complexes, seed treatment protocols, and nursery practices [70, 71, 117, 121]. Short-term research should prioritize region-specific integrated pest and disease management (IPDM) strategies combining host resistance, biological control, and agronomic practices. Long-term research should aim to develop predictive pest and disease models and optimize seed health management for large-scale adoption. Addressing these gaps is likely to have one of the highest impacts on yield stability and smallholder confidence.

3.7.1.4 Environmental and climate assessments There is a critical need for quantitative data on *Medicago sativa*'s environmental contributions. Short-term studies should measure nitrogen fixation efficiency, soil carbon sequestration, and impacts on enteric methane and nitrous oxide emissions under varied management regimes [20]. Long-term research could include life-cycle assessments and modeling the interactions of forage systems with landscape-scale biogeochemical cycles, informing climate-smart policies and payments for ecosystem services.

3.7.1.5 Socio-economic and adoption research Socio-economic barriers, including seed accessibility, input costs, labor requirements, and weak market linkages, remain key adoption constraints [122–124]. Short-term research should focus on participatory and gender-sensitive adoption studies, farmer field schools, and cooperative-based business models to identify barriers and test scalable solutions. Long-term priorities include market develop-

ment, value chain analyses, and integration of *Medicago sativa* into national agricultural policy frameworks, ensuring sustainability and farmer profitability.

3.7.2 Policy implications and priority actions

1. **Seed Systems and Quality Assurance:** National and regional policies must prioritize certified seed multiplication, public–private seed partnerships, and decentralized community-based seed production. Ensuring affordable, high-quality seed and effective inoculants is essential to reduce establishment risks and accelerate adoption [125, 126].
2. **Extension, Capacity Building, and Demonstration Programs:** Scaling *Medicago sativa* adoption requires training farmers on IPDM, inoculation, forage conservation, and anti-bloat management. Farmer-to-farmer learning networks and demonstration plots should be prioritized to enhance confidence and knowledge transfer, especially in regions with limited forage experience.
3. **Financial Incentives and Market Development:** Blended finance, targeted input subsidies, and payments for ecosystem services can de-risk early adoption of perennial forages. Developing value chains for hay, silage, seed, and processed feeds ensures farmers capture added value and supports rural livelihoods.
4. **Water and Land Policy Integration:** Policies must promote efficient irrigation scheduling, drought-tolerant cultivars, and forage use on marginal lands, aligning forage production with sustainable land and water management objectives.
5. **Research-to-Policy Platforms and Multi-Stakeholder Coordination:** National coordination mechanisms connecting breeders, agronomists, extension agents, policy-makers, farmer organizations, and private sector actors are essential to ensure breeding and management research responds to on-farm realities.
6. **Monitoring, Evaluation, and Adaptive Governance:** Institutionalizing monitoring frameworks using remote sensing and farm surveys will track adoption, environmental impact, and socio-economic outcomes, enabling adaptive governance and evidence-based policy adjustments.

4 Conclusions

Medicago sativa emerges as a cornerstone species for climate-smart agriculture and sustainable livestock production due to its multifunctional agronomic, nutritional, and ecological attributes. Its deep-rooting perennial habit, high biomass and protein yield, and efficient nitrogen-fixing capacity enhance soil fertility, water-use efficiency, and carbon sequestration, while supporting resilient livestock systems with improved productivity and feed quality. The crop's adaptability to diverse soils, climates, and management systems, coupled with its integration potential in intercropping, rotation, and irrigated systems, underscores its role in bridging seasonal feed gaps and mitigating climate risks. Despite challenges related to pests, diseases, establishment, anti-nutritional factors, and limited adoption in smallholder systems, strategic interventions including

stress-tolerant cultivar development, improved seed systems, participatory agronomy, integrated pest and disease management, and policy support can unlock its full potential. Therefore, advancing research on breeding, genomics, mixed cropping optimization, and socio-economic scaling, alongside targeted extension, market development, and ecosystem-based management, is essential to harness *Medicago sativa* as a climate-resilient, high-value forage that simultaneously promotes livestock productivity, soil sustainability, and greenhouse gas mitigation, making it a pivotal component of sustainable agricultural landscapes worldwide.

Author contributions

Alemu Gashe Desta wrote the main manuscript text, prepared figures, reviewed the manuscript.

Funding

No funding was received for this research.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable. This study did not involve human participants.

Consent for publication

Not applicable. This study does not contain any individual person's data in any form (including individual details, images, or videos).

Competing interests

The authors declare no competing interests.

Received: 11 September 2025 Accepted: 18 February 2026

Published online: 21 April 2026

References

1. Koutchoro AM, Ranaivoson L, Yaoitcha AS, Houessou LG, Yemadje PL, Biaou SSH. Forage production in West Africa: systematic review of advances, challenges, and perspectives for resilient agropastoral systems. *J Agric Food Res*. 2025. <https://doi.org/10.1016/j.jafr.2025.101941>.
2. Calleja-Satrustegui A, Echeverría A, Ariz I, de Peralta Andrés J, González EM. Unlocking nature's drought resilience: a focus on the parsimonious root phenotype and specialised root metabolism in wild *Medicago* populations. *Plant Soil*. 2024. <https://doi.org/10.1007/s11104-024-06943-w>.
3. Zhang R, Shen Y, He J, Zhang C, Ma Y, Sun C, et al. Nodule-specific cysteine-rich peptide 343 is required for symbiotic nitrogen fixation in *Medicago truncatula*. *Plant Physiol*. 2023;193(3):1897–912. <https://doi.org/10.1016/j.jafr.2025.101941>.
4. Wang X, Ding T, Li Y, Guo Y, Li Y, Duan T. Dual inoculation of alfalfa (*Medicago sativa* L.) with *Funnelliformis mosseae* and *Sinorhizobium medicae* can reduce Fusarium wilt. *J Appl Microbiol*. 2020;129(3):665–79. <https://doi.org/10.1111/jam.14645>.
5. Baidoo MM, Islam MA, Atiemo MB, Munkaila M, Shilpakar C. Phosphorus and potassium management in alfalfa production under varied calcium and magnesium soil conditions with harvesting regimes. *Crop Sci*. 2025;65(3):e70065. <https://doi.org/10.1002/csc2.70065>.
6. Hidosa D, Minota M, Tadele A, Ayele B, Getaneh D. Dry matter yield and quality potential of alfalfa (*medicago sativa*) varieties under irrigation in the Lower Omo Valley of South Ethiopia to alleviate livestock feed shortage. *Cogent Food Agric*. 2025;11(1):2540162. <https://doi.org/10.1080/23311932.2025.2540162>.
7. Acharya JP, Lopez Y, Gouveia BT, de Bem Oliveira I, Resende J, Muñoz PR, et al. Breeding alfalfa (*Medicago sativa* L.) adapted to subtropical agroecosystems. *Agronomy*. 2020;10(5):742. <https://doi.org/10.3390/agronomy10050742>.
8. Fang L, Liu T, Li M, Dong X, Han Y, Xu C, et al. MODMS: a multi-omics database for facilitating biological studies on alfalfa (*Medicago sativa* L.). *Hortic Res*. 2024;11(1):uhad245. <https://doi.org/10.1093/hr/uhad245>.

9. Yu T, Hao F, Gao K, Xiong M, An H. Productivity, soil fertility and enzyme activity of mixed forage grasslands improved by alfalfa and nitrogen addition in Horqin Sandy Land, China. *Sci Rep.* 2025;15(1):10748. <https://doi.org/10.1038/s41598-025-95622-6>.
10. Wang Y, Zhang J, He C, Meng P, Wang J, Gao J, et al. Effects of intercropping and mowing frequency on biological nitrogen fixation capacity, nutritive value, and yield in alfalfa (*Medicago sativa* L. cv. Vernal). *Plants.* 2025;14(2):240. <https://doi.org/10.3390/plants14020240>.
11. Montenegro LF, Descalzo AM, Cunzolo SA, Pérez CD. Modification of the content of n-3 highly unsaturated fatty acid, chemical composition, and lipid nutritional indices in the meat of grass carp (*Ctenopharyngodon idella*) fed alfalfa (*Medicago sativa*) pellets. *J Anim Sci.* 2020;98(4):skaa084. <https://doi.org/10.1093/jas/skaa084>.
12. Kumar S, Kumar A, Nayal S, Shukla A, Kaikhura S. A comprehensive review on possible synergistic therapeutic effects and comparison between phytochemical and nutritional profile of *medicago sativa* and *Panax ginseng*. *Pharmacogn Mag.* 2023;19(4):799–810. <https://doi.org/10.1177/09731296231197306>.
13. Murod M, Suwignyo B, Ariyadi B. The effect of tropical alfalfa (*Medicago sativa* L. cv Kacang Ratu BW) supplementation on performance, intestinal histomorphology, and nutrient digestibility in hybrid ducks: Veterinary Integrative Sciences. *Vet Integr Sci.* 2025;23(1):1–14. <https://doi.org/10.12982/VIS.2025.008>.
14. Tiruneh AT, Amsalu D, Adane K. Effects of variety and cutting interval on agronomic performance and chemical composition of alfalfa (*Medicago Sativa* L.) under irrigation in Central Gondar Zone, Ethiopia. *Trop Subtrop Agroecosyst.* 2025. <https://doi.org/10.56369/tsaes.5538>.
15. Putnam DH. Factors influencing yield and quality in alfalfa. In: Yu LX, Kole C, editors. *The alfalfa genome*. Cham: Springer; 2021. p. 13–27.
16. Sheaffer CC, Evers GW, Jungers JM. Cool-season legumes for humid areas. *Forages Sci Grassland Agric.* 2020;2:263–75. <https://doi.org/10.1002/9781119436669.ch14>.
17. Medina CA, Samac DA, Yu L-X. Pan-transcriptome identifying master genes and regulation network in response to drought and salt stresses in Alfalfa (*Medicago sativa* L.). *Sci Rep.* 2021;11(1):17203. <https://doi.org/10.1038/s41598-021-96712-x>.
18. Chen L, Bao X, Guo G, Huo W, Li Q, Xu Q, et al. Evaluation of gallnut tannin and *Lactobacillus plantarum* as natural modifiers for alfalfa silage: ensiling characteristics, in vitro ruminal methane production, fermentation profile and microbiota. *J Appl Microbiol.* 2022;132(2):907–18. <https://doi.org/10.1111/jam.15246>.
19. Han B, Dong X, Li M, Wang Z, Shi C, Zhou Q, et al. Morphological diversity variation of seed traits among 587 germplasm resources of *Medicago* Genus and 32 germplasm resources of *Trigonella* Genus. *Sci Rep.* 2025;15(1):3059. <https://doi.org/10.1038/s41598-025-87185-3>.
20. Zhang F, Long R, Ma Z, Xiao H, Xu X, Liu Z, et al. Evolutionary genomics of climatic adaptation and resilience to climate change in alfalfa. *Mol Plant.* 2024;17(6):867–83. <https://doi.org/10.1016/j.molp.2024.04.013>.
21. Lin S, Medina CA, Wang G, Combs D, Shewmaker G, Fransen S, et al. Identification of genetic loci associated with five agronomic traits in alfalfa using multi-environment trials. *Theor Appl Genet.* 2023;136(5):121. <https://doi.org/10.1007/s00122-023-04364-4>.
22. Bellabarba A, Decorosi F, Fagorzi C, El Hadj Mimoune A, Buccioni A, Santoni M, et al. Salt stress highlights the relevance of genotype × genotype interaction in the nitrogen-fixing symbiosis between *sinorhizobium meliloti* and alfalfa. *Soil Syst.* 2023;7(4):112. <https://doi.org/10.3390/soilsystems7040112>.
23. Jawla LS, Ondiek JO, Kemboi F. The effects of *Moringa oleifera* (L.) and *Medicago sativa* (L.) supplementation on milk yield and composition in tropical dairy: a review. *GSAR J Agric Vet Sci.* 2025;2(1):08–13.
24. Bozhilova-Sakova M. Forage crops and their application in livestock breeding. *Bulgarian J Animal Husb.* 2025;62(4):37–48.
25. Du W, Huang H, Wang Z-Y, Yang G, Pang Y. The calcium-regulated kinase MsCIPK4 confers drought and salt stress tolerance in alfalfa by enhancing ROS scavenging. *Plant Sci.* 2025. <https://doi.org/10.1016/j.plantsci.2025.112646>.
26. Ilić A, Uhlarik A, Mamlić Z. Drought stress and production of legumes in Europe. In: Nadeem MA, Baloch FS, Bantis F, Fiaz S, Aasim M, editors. *Marker-assisted breeding in legumes for drought tolerance*. Singapore: Springer; 2025. p. 77–105.
27. Humphries AW, Ovalle C, Hughes S, del Pozo A, Inostroza L, Barahona V, et al. Characterization and pre-breeding of diverse alfalfa wild relatives originating from drought-stressed environments. *Crop Sci.* 2021;61(1):69–88. <https://doi.org/10.1002/csc2.20274>.
28. Mekhloufi MB, Rehia A. Adaptations and resistance to salinity stress in forage plants: comparative study of *Medicago sativa* varieties in steppe ecosystems. *Egypt J Agron.* 2025;47(2):339–49.
29. Mekhloufi M. Adaptation and salinity stress resistance in forage crops: a comparative study of *Medicago sativa* varieties in steppe ecosystems. *Egypt J Agron.* 2025. <https://doi.org/10.21608/agro.2025.337579.1566>.
30. Wang Y, He C, Meng P, Sun S, Gao J, Zhang J, et al. Effects of different moisture conditions on biological nitrogen fixation capacity and nutritive value of alfalfa (*Medicago sativa* L.) seedlings. *J Soil Sci Plant Nutr.* 2024;24(4):8235–47. <https://doi.org/10.1007/s42729-024-02109-w>.
31. Stanciu A-Ş. Sustainable forage yield improvement through perennial grass–legume intercropping in degraded grasslands. *Turk J Agric For.* 2025;49(2):215–41. <https://doi.org/10.55730/1300-011X.3261>.
32. Ahmed M, Ahmad S, Abbas G, Hussain S, Hoogenboom G. Alfalfa System. In: Ahmed M, Ahmad S, Abbas G, Hussain S, Hoogenboom G, editors. *Cropping systems modeling under changing climate*. Singapore: Springer; 2024. p. 361–78.
33. Lv M, Tian D, Wang G, Fan T, Li W, Hou C, et al. Selection of alfalfa water and nitrogen management regimes based on the DSSAT model. *Sci Rep.* 2025;15(1):12108. <https://doi.org/10.1038/s41598-025-92058-w>.
34. Lagrange SP, MacAdam JW, Villalba JJ. The use of temperate tannin containing forage legumes to improve sustainability in forage–livestock production. *Agronomy.* 2021;11(1):2264. <https://doi.org/10.3390/agronomy11112264>.
35. Mueller-Harvey I, Bee G, Dohme-Meier F, Hoste H, Karonen M, Kölliker R, et al. Benefits of condensed tannins in forage legumes fed to ruminants: importance of structure, concentration, and diet composition. *Crop Sci.* 2019;59(3):861–85. <https://doi.org/10.2135/cropsci2017.06.0369>.

36. Liu C, Qu Y-h, Guo P-t, Xu C-c, Ma Y, Luo H-l. Effects of dietary supplementation with alfalfa (*Medicago sativa* L.) saponins on lamb growth performance, nutrient digestibility, and plasma parameters. *Anim Feed Sci Technol*. 2018;236:98–106. <https://doi.org/10.1016/j.anifeedsci.2017.12.006>.
37. Muir JP, Batista Dubeux Junior JC, Santos MVF, Foster JL, Caraciolo Ferreira RL, Lira MA, et al. Sustainable warm-climate forage legumes: versatile products and services. *Grasses*. 2025;4(2):16. <https://doi.org/10.3390/grasses4020016>.
38. Akchaya K, Parasuraman P, Pandian K, Vijayakumar S, Thirukumaran K, Mustaffa MRAF, et al. Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: a review. *Front Sustain Food Syst*. 2025;9:1527256. <https://doi.org/10.3389/fsufs.2025.1527256>.
39. Abusaief HMA-A, Boasoul SH. A taxonomic study of twelve wild forage species of Fabaceae. *Heliyon*. 2021. <https://doi.org/10.1016/j.heliyon.2021.e06077>.
40. Chand S, Roy AK, Singh T, Agrawal RK, Yadav VK, Kumar S, et al. Twenty-four years lucerne (*Medicago sativa* L.) breeder seed production in India: a retrospective study. *Front Plant Sci*. 2023;14:1259967. <https://doi.org/10.3389/fpls.2023.1259967>.
41. Wang S-Y, Yang G-L, Jing Y-Y, He Z-N, Liu B, Sun L, et al. Alfalfa quality improvement and loss reduction technology advances. *Front Anim Sci*. 2025;6:1550492. <https://doi.org/10.3389/fanim.2025.1550492>.
42. Henareh J, Ahmadloo F, Pato M. Evaluation of yield and financial advantage of intercropping of poplar (*Populus nigra* 62/154) with alfalfa (*Medicago sativa* L.) at Saatlou poplar research station of Urmia. *For Res Dev*. 2025;10(4):453–77. <https://doi.org/10.30466/jfrd.2024.55437.1733>.
43. Tufail MS, Krebs GL, Quddus MS, Southwell A, Piltz JW, Norton MR, et al. Empowering smallholder farmers by integrating participatory research and establishing village-based forage seed enterprises to enhance on-farm productivity and local seed supply. 2025. *Seeds*. <https://doi.org/10.3390/seeds4030040>.
44. Aravindakshan S, Krupnik TJ, Amjath-Babu T, Speelman S, Tur-Cardona J, Tiltonell P, et al. Quantifying farmers' preferences for cropping systems intensification: a choice experiment approach applied in coastal Bangladesh's risk prone farming systems. *Agric Syst*. 2021;189:103069. <https://doi.org/10.1016/j.agry.2021.103069>.
45. Carlini B, Lucini C, Velázquez J. The role of legumes in the sustainable Mediterranean diet: analysis of the consumption of legumes in the Mediterranean population over the last ten years a PRISMA statement methodology. *Sustainability*. 2024;16(7):3081. <https://doi.org/10.3390/su16073081>.
46. Zhu X, Wei B, Wang B, Wei X. The study on the function of exogenous NO-mediated miR166e-5p in regulating the drought resistance of alfalfa. *Plant Physiol Biochem*. 2025. <https://doi.org/10.1016/j.plaphy.2025.110083>.
47. Koç ÜG, İlhan D. CaO nanoparticles improve salt stress tolerance in diploid and tetraploid alfalfa (*Medicago sativa* L.) by modulating miRNA expression and physiological responses. *Plant Cell Tissue Organ Cult (PCTOC)*. 2025;160(3):75. <https://doi.org/10.1007/s11240-025-02969-9>.
48. Deng X, Wang X, Yang Y, Li J, Gao Y, Huang H, et al. Global research trends and hotspots in white clover (*Trifolium repens* L.) responses to drought stress (1990–2024). *Sustainability*. 2025. <https://doi.org/10.3390/su17051883>.
49. Jiang X-Q, Zhang F, Jiang X. Detection of quantitative trait loci (QTL) associated with spring regrowth in alfalfa (*Medicago sativa* L.). *J Integr Agric*. 2022;21(3):812–8. [https://doi.org/10.1016/S2095-3119\(21\)63671-7](https://doi.org/10.1016/S2095-3119(21)63671-7).
50. Tedesco D, Nieto L, Hernández C, Rybecky JF, Min D, Sharda A, et al. Remote sensing on alfalfa as an approach to optimize production outcomes: a review of evidence and directions for future assessments. *Remote Sens*. 2022;14(19):4940. <https://doi.org/10.3390/rs14194940>.
51. Xu L. Key Ecophysiological Adaptations of Alfalfa (*Medicago sativa* L.) to Saline Environments: paving the Way for Salinity-Smart Crop Development. 2025. eSearch output: Thesis › Thesis fully internal (DIV).
52. Liu H, Li X, Zi Y, Zhao G, Zhu L, Hong L, et al. Characterization of the heat shock transcription factor family in *Medicago sativa* L. and its potential roles in response to abiotic stresses. *Int J Mol Sci*. 2023;24(16):12683. <https://doi.org/10.3390/ijms241612683>.
53. Gonzalez EA, Insausti MCP, Zapico MG, Malena A, Pedranzani HE. Ceba de Sinorhizobium meliloti halotolerante confiere tolerancia a la salinidad a *Medicago sativa* L. *Avances en Investigación Agropecuaria*. 2023;27(1):197–207. <https://doi.org/10.53897/RevAIA.23.27.70>.
54. Zhang Y, Liu G, Lu Q, Xiong D, Li G, Du S. Understanding the limiting climatic factors on the suitable habitat of Chinese Alfalfa. *Forests*. 2022;13(3):482. <https://doi.org/10.3390/f13030482>.
55. Muir JP, Pitman WD, Dubeux JJC, Foster JL. The future of warm-season, tropical and subtropical forage legumes in sustainable pastures and rangelands. *Afr J Range Forage Sci*. 2014;31(3):187–98. <https://doi.org/10.2989/10220119.2014.884165>.
56. Inostroza L, Espinoza S, Barahona V, Gerding M, Humphries A, Del Pozo A, et al. Phenotypic diversity and productivity of *Medicago sativa* subspecies from drought-prone environments in Mediterranean type climates. *Plants*. 2021;10(5):862. <https://doi.org/10.3390/plants10050862>.
57. Baron VS, Bélanger G. Climate, climate-change and forage adaptation. *Forages Sci Grassland Agric*. 2020;2:151–86. <https://doi.org/10.1002/9781119436669.ch8>.
58. Guerchi A, Mnafigui W, Jabri C, Merghni M, Sifaoui K, Mahjoub A, et al. Improving productivity and soil fertility in *Medicago sativa* and *Hordeum marinum* through intercropping under saline conditions. *BMC Plant Biol*. 2024;24(1):158. <https://doi.org/10.1186/s12870-024-04820-3>.
59. Annicchiarico P, Nazzicari N, Pecetti L. Genomic selection for higher yield and quality in alfalfa. In: Yu LX, Kole C, editors. *The alfalfa genome*. Cham: Springer; 2021:191–210. https://doi.org/10.1007/978-3-030-74466-3_12.
60. Lin S, Norberg S, Combs D. Genomics of forage quality in Alfalfa. In: Yu LX, Kole C, editors. *The alfalfa genome*. Cham: Springer; 2021. p. 129–43.
61. Zhang Y, Wang L. Advances in basic biology of alfalfa (*Medicago sativa* L.): a comprehensive overview. *Hortic Res*. 2025;12(7):uhaf081. <https://doi.org/10.1093/hr/uhaf081>.
62. Souza R, Edvan R, Fontes L, Dias e Silva T, da Silva A, Araújo M, et al. Morphological and productive characteristics and chemical composition of grasses in degraded areas subjected to pasture recovery methods. *Grasses*. 2023;2(1):1–11. <https://doi.org/10.3390/grasses2010001>.

63. Reddy NK, Rakhonde G, Purushotham P, Patel PS, Ahale S. Impact of climate change on forage crop production with special emphasis on diseases and mitigation strategies through breeding and molecular approaches. In: Singhal RK, Ahmed S, Pandey S, Chand S, editors. Molecular interventions for developing climate-smart crops: a forage perspective. Singapore: Springer; 2023. p. 75–97.
64. Xu L, Ye L, Nie Y, Yang G, Xin X, Yuan B, et al. Sown alfalfa pasture decreases grazing intensity while increasing soil carbon: experimental observations and DNDC model predictions. *Front Plant Sci.* 2022;13:1019966. <https://doi.org/10.3389/fpls.2022.1019966>.
65. Xu Y, Duan X, Wu Y, Huang H, Fu T, Chu H, et al. Carbon sequestration potential and its main drivers in soils under alfalfa (*Medicago sativa* L.). *Sci Total Environ.* 2024;935:173338. <https://doi.org/10.1016/j.scitotenv.2024.173338>.
66. Xue Z, Wang Y, Palmer E, Zhang Y. Intercropping of orchardgrass and alfalfa improves soil fertility, forage yield, feeding values and land use efficiency while limiting ruminal greenhouse gas emissions. *Grass Forage Sci.* 2023;78(2):275–87. <https://doi.org/10.1111/gfs.12602>.
67. Scoresby D, Teixeira IA, Chahine M. Effects of corn silage and alfalfa hay on production and nitrogen excretion in lactating dairy cows. *Nitrogen.* 2025;6(2):43. <https://doi.org/10.3390/nitrogen6020043>.
68. Baidoo MM, Islam MA. Optimizing potassium applications and harvest strategies to boost productivity of depleting alfalfa stands. *Agron J.* 2025;117(1):e21724. <https://doi.org/10.1002/agj2.21724>.
69. Achli S, Ongoma V, Epule TE, Dhiba D, Salih W, Ousayd L, et al. Exploring the key drivers of crop yields in Morocco—a systematic review. *Front Agron.* 2025;7:1515938. <https://doi.org/10.3389/fagro.2025.1515938>.
70. Yang B, Zhao Y, Guo Z. Research progress and prospect of alfalfa resistance to pathogens and pests. *Plants.* 2022. <https://doi.org/10.3390/plants11151923>.
71. Burezaq H. Diseases infesting forage alfalfa (*Medicago sativa* L.) and management. *Indian J Ecol.* 2023;50(4):1233–44. <https://doi.org/10.55362/IJE/2023/4042>.
72. Miao X, Wang G, Xu B, Li R, Tian D, Ren J, et al. Study on alfalfa water use efficiency and optimal irrigation strategy in Agro-Pastoral Ecotone, Northwestern China. *Agronomy.* 2025;15(2):258. <https://doi.org/10.3390/agronomy15020258>.
73. Jiang Y, Zhou J, Chen X, Kang Y, Yan T, Hou F. Effect of alfalfa hay quality in an alfalfa–maize diet on the digestion, metabolism, and growth rate of goats in the Longdong Loess Plateau. *Grassl Res.* 2025. <https://doi.org/10.1002/ghr2.70009>.
74. Zhu X, Chen W, Li M, Liu B, Zhao S, Hu M, et al. Comprehensive evaluation of the nutritional value and contaminants of alfalfa (*Medicago sativa* L.) in China. *Front Nutr.* 2025;12:1539462. <https://doi.org/10.3389/fnut.2025.1539462>.
75. Tucak M, Ravlić M, Horvat D, Čupić T. Improvement of forage nutritive quality of alfalfa and red clover through plant breeding. *Agronomy.* 2021;11(11):2176. <https://doi.org/10.3390/agronomy11112176>.
76. Chen Y, Xu M, Huang C. Study of the effects of alfalfa bioactive substances and polysaccharides on the lactation performance and immune function of dairy cows. *Indian J Animal Res.* 2025. <https://doi.org/10.18805/IJAR.BF-1878>.
77. Zhang L, Jiang Y, Yin M, Ling Y, Li H, Gan Y, et al. Optimizing phosphorus fertilization management is conducive to improving alfalfa yield and quality: a meta-analysis. *Agriculture.* 2025;15(8):797. <https://doi.org/10.3390/agriculture15080797>.
78. Bionaz M. Feeding spent hemp biomass to dairy cattle. 2021. <https://www.cabidigitallibrary.org/action/doSearch?do=29th+Annual+Tri-State+Dairy+Nutrition+Conference%2C+19-21+April+2021+%28virtual%29>.
79. Kaithwas M, Singh S, Prusty S, Mondal G, Kundu S. Evaluation of legume and cereal fodders for carbohydrate and protein fractions, nutrient digestibility, energy and forage quality. *Range Manage Agrofor.* 2020;41(1):126–32.
80. Bo PT, Dong Y, Zhang R, Soe Htet MN, Hai J. Optimization of alfalfa-based mixed cropping with winter wheat and ryegrass in terms of forage yield and quality traits. *Plants.* 2022;11(13):1752. <https://doi.org/10.3390/plants11131752>.
81. Chauhan K, Sreeja S. Dietary supplementation of poultry for designer egg production: a review. *Asian J Adv Agric Res.* 2025;25(3):74–89. <https://doi.org/10.9734/ajaar/2025/v25i3594>.
82. Kang D, Lungu SE, Danso F, Dzou CF, Chen Y, Zheng X, et al. Animal health and nutrition: metabolic disorders in cattle and improvement strategies. *Front Vet Sci.* 2025;12:1470391. <https://doi.org/10.3389/fvets.2025.1470391>.
83. Brinsi C, Jedidi S, Dhiffalah A, Selmi H, Hammari H, Sebai H. Nutritional value, phytochemical properties of different parts of dill (*Anethum graveolens* L.) and their effects on in vitro digestibility in ruminants. *Nat Prod Commun.* 2024;19(10):1934578X241288854. <https://doi.org/10.1177/1934578X241288854>.
84. Reed K. Fertility of herbivores consuming phytoestrogen-containing *Medicago* and *Trifolium* species. *Agriculture.* 2016;6(3):35. <https://doi.org/10.3390/agriculture6030035>.
85. Wyse JM, Latif S, Gurusinge S, Berntsen ED, Weston LA, Stephen CP. Characterization of phytoestrogens in *Medicago sativa* L. and grazing beef cattle. *Metabolites.* 2021;11(8):550. <https://doi.org/10.3390/metabo11080550>.
86. Blázovics A, Csorba B, Ferencz A. The beneficial and adverse effects of phytoestrogens. *OBM Integr Complementary Med.* 2022;7(3):1–35. <https://doi.org/10.21926/obm.icm.2203034>.
87. Tucker JJ, Mullenix MK, Rios E, Basigalup D, Bouton J. Systems management strategies for increasing alfalfa use in warm-humid regions. *Grassl Res.* 2024;3(2):187–98. <https://doi.org/10.1002/ghr2.12080>.
88. Cireşan C-A, Cocan I, Alexa E, Cărpinişan L, Sîrbu CB, Obîştioiu D, et al. Research on the control of gastrointestinal strongyles in sheep by using *Lotus corniculatus* or *Cichorium intybus* in feed. *Pathogens.* 2023;12(8):986. <https://doi.org/10.3390/pathogens12080986>.
89. Shah SS, Shi L, Li Z, Ren G, Zhou B, Qin P. Yield, agronomic and forage quality traits of different quinoa (*Chenopodium quinoa* Willd.) genotypes in northeast China. *Agronomy.* 2020;10(12):1908. <https://doi.org/10.3390/agronomy10121908>.

90. Viti C, Bellabarba A, Daghighi M, Mengoni A, Mele M, Buccioni A, et al. Alfalfa for a sustainable ovine farming system: proposed research for a new feeding strategy based on alfalfa and ecological leftovers in drought conditions. *Sustainability*. 2021;13(7):3880. <https://doi.org/10.3390/su13073880>.
91. Creech JD, Foster S, editors. Long term trends and the future of the Alfalfa & Forage Industry. Proceedings of the 2013 Western Alfalfa & Forage Symposium. 2013.
92. Undersander D. Economic importance, practical limitations to production, management, and breeding targets of alfalfa. In: Yu LX, Kole C, editors. *The Alfalfa Genome*. Cham: Springer; 2021. p. 1–11.
93. Wang Y, Li M, Guo J, Yan H. Alfalfa (*Medicago sativa* L.) nitrogen utilization, yield and quality respond to nitrogen application level with center pivot fertigation system. *Agronomy*. 2023;14(1):48. <https://doi.org/10.3390/agronomy14010048>.
94. Zhang M, Peng C, Sun W, Dong R, Hao J. Effects of variety, plant location, and season on the phyllosphere bacterial community structure of alfalfa (*Medicago sativa* L.). *Microorganisms*. 2022;10(10):2023. <https://doi.org/10.3390/microorganisms10102023>.
95. Chen R, Chen Y, Lin K, Ding Y, Liu W, Wang S. Growth, quality, and nitrogen metabolism of *Medicago sativa* under continuous light from red–blue–green LEDs responded better to high nitrogen concentrations than under red–blue LEDs. *Int J Mol Sci*. 2024;25(23):13116. <https://doi.org/10.3390/ijms252313116>.
96. Ivanova E, Skaložub O. Variety and microbial nitrogen-fixing preparations in the yield formation of variegated alfalfa. *IOP Conf Ser Earth Environ Sci*. 2021. <https://doi.org/10.1088/1755-1315/723/2/022032>.
97. Wang L, Ali G, Wang Z. Deep soil water depletion and soil organic carbon and total nitrogen accumulation in a long-term alfalfa pasture. *Land Degrad Dev*. 2023;34(8):2164–76. <https://doi.org/10.1002/ldr.4597>.
98. Lu Q, Qi G, Yin M, Kang Y, Ma Y, Jia Q, et al. Alfalfa cultivation patterns in the Yellow River Irrigation Area on soil water and nitrogen use efficiency. *Agronomy*. 2024;14(4):874. <https://doi.org/10.3390/agronomy14040874>.
99. Bucciarelli B, Xu Z, Ao S, Cao Y, Monteros MJ, Topp CN, et al. Phenotyping seedlings for selection of root system architecture in alfalfa (*Medicago sativa* L.). *Plant Methods*. 2021;17(1):125. <https://doi.org/10.1186/s13007-021-00825-3>.
100. Tharindi P, De Silva S, Thakshila GI, Sandamal S, Rathnayake RS, Hisanithy P, et al. Perennial forage crops: biodiversity and ecosystems service in Barren Land. In: Singhal RK, El Sabagh AI, Dwivedi KK, editors., et al., *Forage crops in the bioenergy revolution: from fields to fuel*. Singapore: Springer; 2025. p. 123–55.
101. Del Pozo A, O valle C, Espinoza S, Barahona V, Gerding M, Humphries A. Water relations and use-efficiency, plant survival and productivity of nine alfalfa (*Medicago sativa* L.) cultivars in dryland Mediterranean conditions. *Eur J Agron*. 2017;84:16–22. <https://doi.org/10.1016/j.eja.2016.12.002>.
102. Ghorbel M, Alghamdi A, Brini F, Hawamda AI, Mseddi K. Mitigating water loss in arid lands: buffelgrass as a potential replacement for alfalfa in livestock feed. *Agronomy*. 2025;15(2):371. <https://doi.org/10.3390/agronomy15020371>.
103. Buzzanca C, D'Amico A, Gabrielli P, Durazzo A, Lucarini M, Di Stefano V. Alfalfa (*Medicago sativa* L.): literature quantitative research analysis. *Nat Prod Res*. 2025. <https://doi.org/10.1080/14786419.2025.2486335>.
104. Medina CA, Hawkins C, Liu X-P, Peel M, Yu L-X. Genome-wide association and prediction of traits related to salt tolerance in autotetraploid alfalfa (*Medicago sativa* L.). *Int J Mol Sci*. 2020;21(9):3361. <https://doi.org/10.3390/ijms21093361>.
105. De Leon VB. Salinity tolerance evaluation of four varieties of alfalfa (*Medicago sativa* L.) and potential effects on forage quality and plant nutritional value. Fresno: California State University; 2024.
106. Poulin A, Charbonneau É, Petri RM, Thériault M, Ouellet D, Tremblay G, et al. Effect of modifying energy to protein ratio of alfalfa on ruminal fermentation, nitrogen use, methane production, and microbial composition in vitro. *Can J Anim Sci*. 2025;105:1–13. <https://doi.org/10.1139/cjas-2024-0097>.
107. Ahmed MG, Al-Sagheer AA, El-Waziry AM, El-Zarkouny SZ, Elwakeel EA. Ensiling characteristics, in vitro rumen fermentation patterns, feed degradability, and methane and ammonia production of berseem (*Trifolium alexandrinum* L.) co-ensiled with artichoke bracts (*Cynara cardunculus* L.). *Animals*. 2023;13(9):1543. <https://doi.org/10.3390/ani13091543>.
108. Symeon GK, Akamati K, Dotas V, Karatosidi D, Bizelis I, Laliotis GP. Manure management as a potential mitigation tool to eliminate greenhouse gas emissions in livestock systems. *Sustainability*. 2025;17(2):586. <https://doi.org/10.3390/su17020586>.
109. Wang Y, He C, Meng P, Sun S, Zhang J, Xue P, et al. Effects of mowing frequency on the interspecific water relationships of a walnut (*Juglans regia* L.)-alfalfa (*Medicago sativa* L.) intercropping system. *Plant Soil*. 2025;509(1):201–20. <https://doi.org/10.1007/s11104-024-06854-w>.
110. Qiao H, Cheng H, Li T, Fan W, Zhao Y, Cui Z, et al. Species interactions shape nitrogen utilization characteristics and influence soil quality in Jujube–Alfalfa intercropping system. *Plants*. 2025;14(13):2048. <https://doi.org/10.3390/plants14132048>.
111. Tlahig S, Neji M, Atoui A, Seddik M, Dbara M, Yahia H, et al. Genetic and seasonal variation in forage quality of lucerne (*Medicago sativa* L.) for resilience to climate change in arid environments. *J Agric Food Res*. 2024;15:100986. <https://doi.org/10.1016/j.jafr.2024.100986>.
112. El Sabagh A, Iqbal MA, Wasaya A, Irfan M, Rajendran K, Zahid R, et al. Strategies to enhance biomass production in forage crops under challenging environments. In: Singhal RK, El-Sabagh AI, Dwivedi KK, editors., et al., *Forage Crops in the bioenergy revolution: from fields to fuel*. Singapore: Springer; 2025. p. 157–82.
113. Ferreira H, Pinto E, Vasconcelos MW. Legumes as a cornerstone of the transition toward more sustainable agri-food systems and diets in Europe. *Front Sustain Food Syst*. 2021;5:694121. <https://doi.org/10.3389/fsufs.2021.694121>.
114. Kanatas P, Gazoulis I, Travlos I. Irrigation timing as a practice of effective weed management in established alfalfa (*Medicago sativa* L.) crop. *Agronomy*. 2021;11(3):550. <https://doi.org/10.3390/agronomy11030550>.
115. Liu X, Elzenga JT, Venema JH, Tiedge KJ. Thriving in a salty future: morpho-anatomical, physiological and molecular adaptations to salt stress in alfalfa (*Medicago sativa* L.) and other crops. *Annals of Botany*. 2024 Dec 16;134(7):1113–30. <https://doi.org/10.1093/aob/mcae152>

116. Khan NA, Haq IU, Ijaz S, Cetinel B. *Medicago sativa*: diseases, etiology, and management. In: Haq I, Ijaz S, editors. Sustainable winter fodder. Boca Raton: CRC Press; 2021. p. 83–110.
117. Larsen L, Dornbusch MR, Hines-Snyder C, Samac D. Assessment of seed treatments for management of pathogens causing seed rot, seedling damping-off, and seedling root rot in alfalfa (*Medicago sativa* L.). *Plant Dis*. 2025. <https://doi.org/10.1094/PDIS-05-24-1147-RE>.
118. Zhang K, Khan Z, Yu Q, Qu Z, Liu J, Luo T, et al. Biochar coating is a sustainable and economical approach to promote seed coating technology, seed germination, plant performance, and soil health. *Plants*. 2022;11(21):2864. <https://doi.org/10.3390/plants11212864>.
119. Cassani MT, Gutknecht JL, Basche A, Brunsell NA, Crews TE, Culman S, et al. Productivity of intermediate wheat-grass responds more to local soil and climate factors than fertility treatments in the first establishment year. *Front Agron*. 2025;7:1528534. <https://doi.org/10.3389/fagro.2025.1528534>.
120. D'Amours E, Bertrand A, Cloutier J, Claessens A, Rocher S, Seguin P. Selection of effective and competitive *Sinorhizobium meliloti* strains that nodulate alfalfa under low temperature. *Rhizosphere*. 2024;29:100860. <https://doi.org/10.1016/j.rhisph.2024.100860>.
121. Caselli A, Petacchi R. Climate change and major pests of mediterranean olive orchards: are we ready to face the global heating? *Insects*. 2021;12(9):802. <https://doi.org/10.3390/insects12090802>.
122. Yeshitila WS. Exploring the seed setting problem in alfalfa (*Medicago Sativa* L.) and its implications for seed production barriers in Sub-Saharan Africa: a review. *Int J Sci Res Eng Dev*. 2025;8(1):273.
123. Silva LS, Mullenix MK, Prevatt C, Tucker JJ. Perceptions of adoption of alfalfa plantings by forage–livestock producers in the southern United States. *Appl Anim Sci*. 2021;37(6):665–9. <https://doi.org/10.15232/aas.2021-02194>.
124. Kebede G, Assefa G, Feyissa F, Faji M, Alemayehu M, Mengistu A, et al. Seed quality in forage crops: current status and gaps in Ethiopia. *OMO Int J Sci*. 2020;3(2):64–83.
125. Enciso K, Triana N, Díaz M, Burkart S. On (dis) connections and transformations: the role of the agricultural innovation system in the adoption of improved forages in Colombia. *Front Sustain Food Syst*. 2022;5:741057. <https://doi.org/10.3389/fsufs.2021.741057>.
126. Chand S, Roy AK, Kumar S, Singh T, Yadav VK, Ramling SS, et al. Quality seed production scenario of Egyptian clover (*Trifolium alexandrinum*) in India: a 24-year retrospective analysis. *Heliyon*. 2024. <https://doi.org/10.1016/j.heliyon.2024.e35735>.
127. Sandhu R, Bangarwa SK, Attri M, Tiwari S, Kohli S, Fayaz S, et al. Effects of biotic stresses and their mitigation strategies in legumes: a review. *Legume Res Int J*. 2025. <https://doi.org/10.18805/LR-5160>.
128. Singh T, Ramakrishnan S, Mahanta SK, Tyagi VC, Roy AK. Tropical forage legumes in India: status and scope for sustaining livestock production. *Forage groups*. 2018;2:166.
129. Assefal G, Berhanu T, Gizachew L, Dejeniet M, Geleti D. Major herbaceous forage legumes: Some achievements in species and varietal evaluation in Ethiopia. *Food and forage legumes of Ethiopia: Progress and prospects*. 2006;291.
130. Dear B, Moore G, Hughes S. Adaptation and potential contribution of temperate perennial legumes to the southern Australian wheatbelt: a review. *Aust J Exp Agric*. 2003;43(1):1–18. <https://doi.org/10.1071/EA01202>.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.